

Paramagnetic Intrinsic Meissner Effect in Layered Superconductors

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Abstract

Free energy of a layered superconductor with $\xi_{\perp} < d$ is calculated in a parallel magnetic field by means of the Gor'kov equations, where ξ_{\perp} is a coherence length perpendicular to the layers and d is an inter-layer distance. The free energy is shown to differ from that in the textbook Lawrence-Doniach model at high fields, where the Meissner currents are found to create an unexpected positive magnetic moment due to shrinking of the Cooper pairs "sizes" by a magnetic field. This paramagnetic intrinsic Meissner effect in a bulk is suggested to detect by measuring in-plane torque, the upper critical field, and magnetization in layered organic and high- T_c superconductors as well as in superconducting superlattices.

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The Meissner diamagnetic effect is known to be the most important property of a superconducting phase and is responsible for destruction of superconductivity both in type-I and type-II superconductors [1]. Meanwhile, as shown by us in Refs. [2-4] and independently by Tesanovic, Rasolt, and Xing in Ref. [5], quantum effects of an electron motion in a magnetic field result in the appearance of a qualitatively different phenomenon - superconductivity surviving in high magnetic fields in layered [2-4] and isotropic three-dimensional [5] type-II superconductors. In particular, it was shown [2-4,6] that in a layered conductor in a parallel magnetic field, where the Landau levels quantization is impossible, some other quantum effects - the Bragg reflections - play an important role. These quantum effects result in a "two-dimensionalization" (i.e., $3D \rightarrow 2D$ dimensional crossover) of an open electron spectrum in an arbitrary weak parallel magnetic field. This is known [6,7] to cause the field-induced spin-density-wave (FISDW) and field-induced charge-density-wave (FICDW) instabilities in layered quasi-one-dimensional (Q1D) conductors. More complicated $3D \rightarrow 1D \rightarrow 2D$ dimensional crossovers are shown [8,9] to be responsible for the experimentally observed non-trivial angular magnetic oscillations in a metallic phase of different layered organic conductors, including Interference Commensurate [8] and Lebed Magic Angle [9] oscillations.

As shown in Refs.[2-4,7], the similar $3D \rightarrow 2D$ dimensional crossovers have to be responsible for a stabilization of a superconducting phase in layered Q1D [2,4] and quasi-two-dimensional (Q2D) [3] conductors since 2D superconductivity is not destroyed in a parallel magnetic field. More precisely, it is shown [2-4] that: (i) the quantum effects make the upper critical field to be divergent, $H_{c2}^{\parallel}(T) \rightarrow \infty$ as $T \rightarrow 0$, and (ii) there is some critical field, H^* , above which superconducting temperature grows in an increasing magnetic field. Such superconducting phase with $dT_c/dH > 0$ is called the Reentrant Superconductivity (RS) [2-5]. The original predictions [2-4] have been theoretically confirmed by a number of studies [10-14], including a study [14], which takes into account a possibility of a pure 2D phase transition. Despite of a great success of $3D \rightarrow 1D \rightarrow 2D$ and $3D \rightarrow 2D$ dimensional crossovers concepts in the explanations of magnetic properties in a metallic [7-9], the FISDW [6,7], and the FICDW [7] phases of organic conductors, so far there has been no evidence that superconducting temperature can grow in high magnetic fields due to the the quantum $3D \rightarrow 2D$ dimensional crossovers [2-5,10-14]. A possibility of the RS phase to exist was experimentally studied in Q1D layered organic superconductors (TMTSF)₂X (X = PF₆ and X = ClO₄) by Naughton's and Chakin's groups [15-17]. Their experiments gave hints on a possibility for superconductivity to exceed significantly the quasi-classical upper critical field $H_{c2}^{\parallel}(0)$ - the effect predicted in Refs.[2-5,10-14] - but they were not able to confirm the appearance of the RS phase with $dT_c/dH > 0$. Analogous experiments, performed on a Q2D superconductor Sr₂RuO₄ [18], did not detect any stabilization of superconductivity at

$$H > H_{c2}^{\parallel}(0).$$

The main obvious difficulty in the above mentioned efforts to discover the RS phase is the Pauli spin-splitting destructive mechanism against superconductivity and the related Clogston paramagnetic limiting field, H_p [1]. It is absent only for some triplet superconducting phases which are believed to exist in $(\text{TMTSF})_2\text{X}$ [2,15,4] and Sr_2RuO_4 [19] superconductors. On the other hand, recently there have appeared the NMR measurements [20] in favor of a singlet nature of superconductivity in $(\text{TMTSF})_2\text{ClO}_4$ material as well as some doubts [21] in a triplet nature of superconductivity in Sr_2RuO_4 one.

The goal of our Letter is a three-fold one. Firstly, we show that, although in layered paramagnetically limited (singlet) superconductors the RS phase may not be characterized by $dT_c/dH > 0$ feature [2-4, 10-14], nevertheless the RS phase reveals itself as another unique phenomenon - paramagnetic intrinsic Meissner effect (PIME). Secondly, we extend microscopical theory [3] to describe the most important from experimental point of view d - and s -wave Q2D superconductors with $\xi_{\perp} < d$, where ξ_{\perp} is a coherence length perpendicular to the conducting layers and d is an inter-layer distance. And thirdly, we suggest simple experimental methods to detect the PIME phenomenon in Q2D organic and high- T_c superconductors by using in-plane torque, the upper critical field, and magnetization measurements. In particular, we demonstrate that in-plane anisotropy due to anisotropic Ginzburg-Landau coherence lengths, which disappears in an intermediate region of magnetic fields (where the Lawrence-Doniach model is applicable), appears again in high magnetic fields as a consequence of the PIME phenomenon (see Figs. 1,2). We suggest to measure in-plane anisotropy of the upper critical field and magnetization as well as in-plane torque in high magnetic fields to discover the PIME and RS phenomena. For these purposes, we derive a free energy of a Q2D superconductor with $\xi_{\perp} < d$ in a parallel magnetic field from the Gor'kov formulation [22-24] of the microscopic superconductivity theory. Our results coincide with that of the Lawrence-Doniach model [25,26] only at low enough magnetic fields, $H \ll H^*$, where the Meissner effect is diamagnetic. We show that, at high magnetic fields, $H \sim H^* \leq H_p$, the field starts to shrink the Cooper pair "sizes" in perpendicular to conducting layers direction due to $3D \rightarrow 2D$ crossovers in a parallel magnetic field. The above mentioned $3D \rightarrow 2D$ crossovers of the Cooper pairs are not taken into account in the Lawrence-Doniach model and, as shown below, are responsible for the unique PIME phenomenon.

Let us consider a layered superconductor with a Q2D electron spectrum,

$$\epsilon(\mathbf{p}) = \epsilon_{\parallel}(p_x, p_y) + 2t_{\perp} \cos(p_z d) , \quad t_{\perp} \ll \epsilon_F , \quad (1)$$

in a parallel magnetic field,

$$\mathbf{H} = (0, H, 0) , \quad \mathbf{A} = (0, 0, -Hx) , \quad (2)$$

where $\epsilon_{\parallel}(p_x, p_y) \sim \epsilon_F$ is in-plane electron energy, t_{\perp} is an overlapping integral of electron wave functions in a perpendicular to the conducting planes direction, ϵ_F is the Fermi energy. Electron spectrum (1) can be linearized near 2D Fermi surface (FS), $\epsilon_{\parallel}(p_x, p_y) = \epsilon_F$, in the following way,

$$\epsilon(\mathbf{p}) - \epsilon_F = v_x(p_y)[p_x - p_x(p_y)] + 2t_{\perp} \cos(p_z d) , \quad (3)$$

where $v_x(p_y) = \partial\epsilon_{\parallel}(p_x, p_y)/\partial p_y$ is a velocity component and $p_x(p_y)$ is the Fermi momentum along x -axis.

In the gauge (2), electron Hamiltonian in a magnetic field can be obtained from Eq.(3) by means of the Peierls substitution method, $p_x \rightarrow -i(d/dx)$, $p_z \rightarrow p_z + (e/c)Hx$ [6]. Therefore, electron Green functions in a magnetic field satisfy the following differential equation,

$$\left\{ i\omega_n - v_x(p_y) \left[-i\frac{d}{dx} - p_x(p_y) \right] + 2t_{\perp} \cos\left(p_z d + \frac{eHdx}{c}\right) + 2\mu_B Hs \right\} \times G_{i\omega_n}(x, x_1; p_y, p_z; s) = \delta(x - x_1) , \quad (4)$$

where ω_n is the Matsubara frequency [22], μ_B is the Bohr magneton, $s = \pm\frac{1}{2}$ is an electron spin projection along quantization y -axis; $\hbar \equiv 1$. It is important that Eq.(4) can be solved analytically. As a result, we obtain,

$$G_{i\omega_n}(x, x_1; p_y, p_z; s) = -i \frac{\text{sgn } \omega_n}{v_x(p_y)} \exp\left[-\frac{\omega_n(x - x_1)}{v_x(p_y)}\right] \exp[ip_x(p_y)(x - x_1)] \times \exp\left[\frac{2i\mu_B s H(x - x_1)}{v_x(p_y)}\right] \exp\left\{\frac{i\lambda(p_y)}{2} \left[\sin\left(p_z d + \frac{eHdx}{c}\right) - \sin\left(p_z d + \frac{eHdx_1}{c}\right) \right]\right\} , \quad (5)$$

where $\lambda(p_y) = 4t_{\perp}c/ev_x(p_y)Hd$.

Linearized gap equation determining superconducting transition temperature, $T_c(H)$, can be derived using Gor'kov equations for non-uniform superconductivity [3,23,24]. As a result, we obtain,

$$\Delta(x) = V \oint \frac{dl}{v_{\perp}(l)} \int_{|x-x_1| > |v_x(l)|/\Omega}^{\infty} dx_1 \frac{2\pi T}{v_x(l) \sinh\left[\frac{2\pi T|x-x_1|}{v_x(l)}\right]} \cos\left[\frac{2\mu_B H(x - x_1)}{v_x(l)}\right] \times J_0\left\{2\lambda(l) \sin\left[\frac{eHd(x - x_1)}{2c}\right] \sin\left[\frac{eHd(x + x_1)}{2c}\right]\right\} \Delta(x_1) , \quad (6)$$

where integration in Eq.(6) is made along 2D contour, $\epsilon_{\parallel}(p_x, p_y) = \epsilon_F$, $v_{\perp}(l)$ is a velocity component perpendicular to the 2D FS, V is an effective electron-electron interactions constant, Ω is a cut-off energy. [Note that, although Eq.(6) is derived for singlet s -wave superconductors, it is also valid for d -wave superconductors [27] if we redefine properly anisotropic coherence lengths and the effective interactions constant V .]

We point out that Eq.(6) is the most general one among the existing equations to determine the parallel upper critical field in a layered superconductor. In particular, it takes into account the Bragg reflections and related $3D \rightarrow 2D$ dimensional crossovers of electrons, which move in the extended Brillouin zone in a parallel magnetic field. As shown in Ref. [7], the above mentioned quantum effects result in a momentum quantization law for an electron momentum component along x -axis. This is a reason why the kernel of the integral Eq.(6) is periodic [2,4] with respect to variables x and x_1 . In the case, where the destructive Pauli spin-splitting effects against superconductivity are absent [i.e., at $\mu_B = 0$ in Eq.(6)], Eq.(6) possesses a periodic solution for $\Delta(x)$ at any magnetic field. In this case, superconductivity is stable in an arbitrary strong magnetic field and exists at high fields in a form of the RS phase with $dT_c/dH > 0$. In the case of a singlet superconductivity, which is considered in the Letter, the Pauli spin-splitting effects may eliminate the superconductivity with $dT_c/dH > 0$. Nevertheless, in the latter case, the RS phase reveals itself as unusual anisotropy of the upper critical field and magnetization in high magnetic fields, $H > H^* \sim (t_\perp/T_c)^{1/2}\phi_0/\xi_x d \ll H_p$ (see Figs. 1,2).

As the most general equation, Eq.(6) contains Ginzburg-Landau and Lawrence-Doniach descriptions as its limiting cases at low enough magnetic fields, $H \ll H^*$. For the so-called Josephson coupled layered superconductors with $\xi_\perp < d$ [25,26], Eq.(6) may be simplified and rewritten in the following differential form,

$$\left[\frac{T_c - T}{T_c} - 2.1 \left(\frac{\mu_B H}{\pi T_c} \right)^2 + \xi_x^2 \frac{d^2}{dx^2} - A(H) + B(H) \cos\left(\frac{2x\omega_c}{v_F}\right) \right] \Delta(x) = 0 \quad (7)$$

with

$$A(H) = \frac{8t_\perp^2}{\omega_c^2} \left\langle \left[\frac{v_F}{v_x(l)} \right]^2 \int_0^\infty \frac{dz}{\sinh(z)} \sin^2 \left[\frac{\omega_c}{4\pi T_c} \frac{v_x(l)}{v_F} z \right] \right\rangle \quad (8)$$

and

$$B(H) = \frac{8t_\perp^2}{\omega_c^2} \left\langle \left[\frac{v_F}{v_x(l)} \right]^2 \int_0^\infty \frac{dz}{\sinh(z)} \sin^2 \left[\frac{\omega_c}{4\pi T_c} \frac{v_x(l)}{v_F} z \right] \cos \left[\frac{\omega_c}{4\pi T_c} \frac{v_x(l)}{v_F} z \right] \right\rangle, \quad (9)$$

where

$$\langle \dots \rangle = \oint \frac{dl}{v_\perp(l)} (\dots) / \oint \frac{dl}{v_\perp(l)}. \quad (10)$$

[Here, $\omega_c = eHv_F d/c$ is a characteristic frequency of an electron motion along open FS (1) [3], $\xi_x = \sqrt{7\zeta(3)} \langle v_x^2(l) \rangle^{1/2} / 4\pi T_c$ is in-plane Ginzburg-Landau coherence length, $\mu_B H \simeq \omega_c(H) \ll \pi T_c$.]

Note that Eqs.(7)-(10) extend the Lawrence-Doniach model [25,26] to the case of strong magnetic fields and can be called extended Lawrence-Doniach equations. In contrast to the traditional Lawrence-Doniach equations, the coefficients $A(H)$ and $B(H)$ in Eqs.(7)-(10) depend on a magnetic field, which means that a probability for the Cooper pair to jump from one conducting layer to another depends on the field. This important feature

of Eqs.(7)-(10) is a consequence of shrinking of the Cooper pairs "sizes" due to $3D \rightarrow 2D$ dimensional crossover in a parallel magnetic field [2,3,7].

Below, we are interested in descriptions of the RS and PIME phenomena, therefore, we consider Eqs.(7)-(10) at high magnetic fields. It is possible to show that at $H \geq H^*$ the solution of Eq.(7) can be represented as $\Delta(x) = \Delta = \text{const}$, which corresponds to the RS phase [2,3]. In this case, the corresponding second order term of a free energy with respect to the order parameter Δ can be written in the following simple form,

$$F^2(T, H) = -N(\epsilon_F) \left[\frac{T_c(H) - T}{T_c} \right] \Delta^2, \quad (11)$$

where

$$T_c(H) = T_c - 2.1 \frac{(\mu_B H)^2}{\pi^2 T_c} - 2.1 \frac{t_\perp^2}{\pi^2 T_c} + 0.95 \frac{t_\perp^2}{\pi^2 T_c} \left(\frac{eHd}{c} \right)^2 \xi_x^2, \quad (12)$$

where $N(\epsilon_F)$ is a density of states per one electron spin projection at $\epsilon = \epsilon_F$.

Note that the the first term in Eq.(12) describes destruction of a singlet superconductivity by the Pauli spin-splitting effects, whereas the last term in Eq.(12) is responsible for the restoration of superconductivity at high magnetic fields and for the appearance of the RS phase and PIME phenomenon. If we take into account that the fourth order term of a free energy with respect to the order parameter Δ can be calculated at $H \geq H^*$ in a standard manner [23], $F^4 = 7\zeta(3)N(\epsilon_F)\Delta^4/16\pi^2 T_c^2$, then we can minimize the total free energy and find that

$$F(T, H) = -\frac{4\pi^2}{7\zeta(3)} N(\epsilon_F) [T_c(H) - T]^2. \quad (13)$$

Magnetization can be found by a differentiation of the free energy (13) with respect to a magnetic field,

$$M(T, H) = -\frac{\partial F(T, H)}{\partial H} = \frac{8}{7\zeta(3)} N(\epsilon_F) \left(\frac{T_c - T}{T_c} \right) \left[-4.2 \mu_B^2 + 1.9 \left(\frac{et_\perp d}{c} \xi_x \right)^2 \right] H, \quad (14)$$

Eqs.(12)-(14) are the main results of the Letter. Note that, in Eq.(14), the first term corresponds to a destruction of superconductivity due to the Pauli spin-splitting effects, whereas the second term represents unusual paramagnetic orbital contribution to a magnetic moment (i.e., the PIME phenomenon). It is important that ξ_x in Eqs.(12)-(14) is anisotropic and depends on a direction of a magnetic field, since it is in-plane component of a coherence length perpendicular to the field. Therefore, the RS and PIME effects in Eqs.(12)-(14) can be detected by measuring a torque provided that spin-splitting effects are isotropic (see Eqs.1,2).

In conclusion, we discuss possible experiments to discover the PIME and RS phenomena. The most direct method is to create such layered superconducting super-lattice, where $\omega_c(H) \gg \mu_B H$ [28]. The latter condition means that the orbital effects are more important

than the Pauli spin-splitting ones. Therefore, in this case, the increase of transition temperature (12) and the paramagnetic Meissner effect (14) can be directly observed. Nevertheless, in most real physical compounds with $\xi_{\perp} < d$, $\omega_c(H) \simeq \mu_B H$ and, thus, the PIME (14) and RS (12) phenomena can be observed only indirectly - by measurements of anisotropies of the in-plane upper critical field (12) and magnetization (14) as well as by measurements of in-plane torque. In our opinion, the most perspective superconductors for indirect observations of the PIME phenomenon in steady magnetic fields are organic compounds α -(ET)₂NH₄Hg(SCN)₄, κ -(ET)₂Cu(NCS)₂, κ -(ET)₂Cu[N(CN)₂]X, α -(ET)₂KHg(SCN)₄, and λ -(BETS)₂FeCl₄ [29]. The above mentioned studies of the in-plane anisotropies can be performed also in high-temperature superconductor Y₁Ba₂C₃O₇ but it will require ultra-high pulsed magnetic fields.

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- [1] A.A. Abrikosov, *Fundamentals of Theory of Metals* (Elsevier Science Publisher B.V., Amsterdam, 1988).
 - [2] A.G. Lebed, Pis'ma Zh. Eksp. Teor. Fiz. 44, 9 (1986) [JETP Lett. 44, 114 (1986)]; L.I. Burlachkov, L.P. Gor'kov, and A.G. Lebed, Europhys. Lett. 4, 941 (1987).
 - [3] A.G. Lebed and K. Yamaji, Phys. Rev. Lett. 80, 2697 (1998).
 - [4] A.G. Lebed, Phys. Rev. B 59, R721 (1999); A.G. Lebed, K. Machida, and M. Ozaki, Phys. Rev. B 62, R795 (2000).
 - [5] M. Rasolt, Phys. Rev. Lett. 58, 1482 (1987); Z. Tesanovic, M. Rasolt, and Lei Xing, Phys. Rev. Lett. 63, 2425 (1989); M. Rasolt and Z. Tesanovic, Rev. Mod. Phys. 64, 709 (1992).
 - [6] L.P. Gor'kov and A.G. Lebed, J. Phys. (Paris) Lett. 45, L433 (1984); P.M. Chaikin, Phys. Rev. B 31, 4770 (1985); M. Heritier, G. Montambaux, and P. Lederer, J. Phys. (Paris) Lett. 45, L943 (1984); A.G. Lebed, Zh. Eksp. Teor. Fiz. 89, 1034 (1985) [Sov. Phys. JETP 62, 595 (1985)].
 - [7] See chapters by A.G. Lebed, by M. Heritier, by A.G. Lebed and Si Wu, and by A. Bjelis and D. Zanchi in *The Physics of Organic Superconductors and Conductors*, edited by A.G. Lebed (Springer-Verlag, Berlin-Heidelberg, in press, 2008).
 - [8] A.G. Lebed and M.J. Naughton, Phys. Rev. Lett. 91, 187003 (2003); A.G. Lebed, Heon-Ick Ha, and M.J. Naughton, Phys. Rev. B 71, 132504 (2005); H.I. Ha, A.G. Lebed, and M.J. Naughton, Phys. Rev. B 73, 033107 (2006).

- [9] A.G. Lebed, N.N. Bagmet, and M.J. Naughton, Phys. Rev. Lett. 93, 157006 (2004).
- [10] N. Dupuis, G. Montambaux, and C.A.R. Sa de Melo, Phys. Rev. Lett. 70, 2613 (1993); N. Dupuis and G. Montambaux, Phys. Rev. B 49, 8993 (1994).
- [11] V.P. Mineev, J. Phys. Soc. Jpn 69, 3371 (2000).
- [12] R.D. Duncan, C.D. Vaccarella, and C.A.R. Sa de Melo, Phys. Rev. B 64, 172503 (2001); C.D. Vaccarella and C.A.R. Sa de Melo, Phys. Rev. B 64, 212504 (2001).
- [13] M. Miyazaki, K. Kishigi, Y. Hasegawa, J. Phys. Soc. Jpn 68, 2344 (1999).
- [14] C.A.R. Sa de Melo and C.D. Vaccarella, Phys. Rev. B 63, 180505 (2001).
- [15] I.J. Lee, M.J. Naughton, G.M. Danner, and P.M. Chaikin, Phys. Rev. Lett. 78, 3555 (1997).
- [16] I.J. Lee, P.M. Chaikin, and M.J. Naughton, Phys. Rev. Lett. 88, 207002 (2002); Phys. Rev. B 65, 180502 (2002).
- [17] For a review, see D. Jerome, Nature 387, 235 (1997).
- [18] E. Ohmichi, S. Nagai, Y. Maeno, et al., Physica B 294, 375 (2001).
- [19] T.M. Rice and M. Sigrist, J. Phys. Condens. Matter 7, L643 (1995).
- [20] J. Shinagawa, Y. Kurosaki, F. Zhang, C. Parker, S.E. Brown, D. Jerome, J.B. Christensen, and K. Bechgaard, Phys. Rev. Lett. 98, 147002 (2007).
- [21] A.G. Lebed and N. Hayashi, Physica C (Amsterdam) 341, 1677 (2000); Igor Zutic and Igor Mazin, Phys. Rev. Lett. 95, 217004 (2005); K. Machida and M. Ichioka, arxiv: 0706.1426 (2007).
- [22] A.A. Abrikosov, L.P. Gor'kov, and I.E. Dzyaloshinskii, *Methods of Quantum Field Theory in Statistical Physics* (Dover Publications, New York, 1963).
- [23] See, for example, V.P. Mineev and K.V. Samokhin, *Introduction to Unconventional Superconductivity* (Gordon and Breach Science Publishers, Australia, 1999).
- [24] See, for example, M. Sigrist and K. Ueda, Rev. Mod. Phys. 63, 239 (1991).
- [25] L.N. Bulaevskii and A.A. Guseinov, Pis'ma Zh. Eksp. Teor. Fiz. 19, 742 (1974) [JETP Lett., 19, 382 (1974)].
- [26] R.A. Klemm, A. Luther, and M.R. Beasley, Phys. Rev. B 12, 877 (1975).
- [27] In this Letter, we calculate the paramagnetic Meissner moment and its two-fold anisotropy. We disregard a weak four-fold anisotropy due to a d -wave gap since it is $(t_{\perp}/T_c)^2 \ll 1$ times smaller than the above calculated two-fold one.
- [28] This idea belongs to P.M. Chaikin (private communication).
- [29] The author is thankful to M.V. Kartsovnik for his help to select the above mentioned layered superconductors, where $\xi_{\perp} \leq d$.

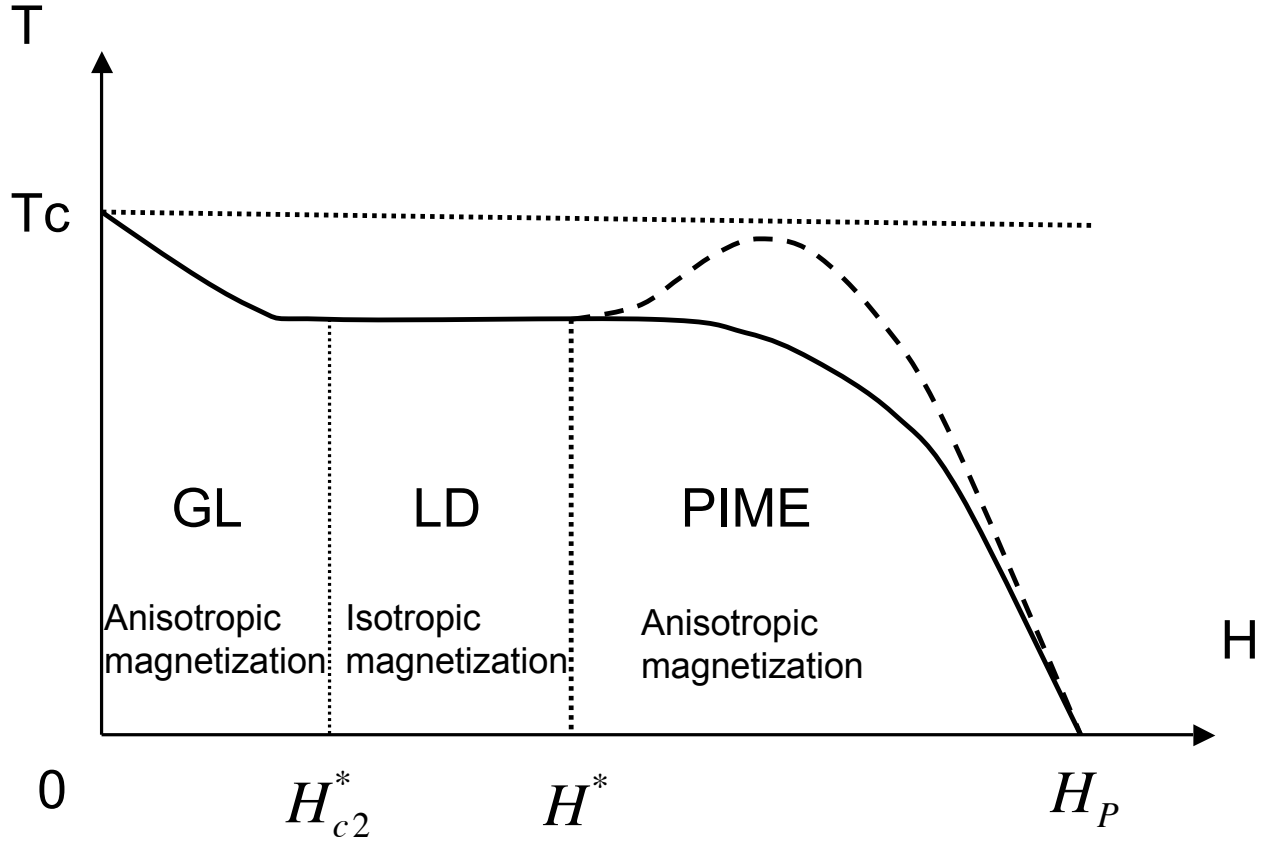


FIG. 1: Superconducting transition temperature in a parallel magnetic field for a paramagnetically limited Q2D superconductor is sketched. GL - area of applicability of the Ginzburg-Landau theory [1], LD - area of applicability of the Lawrence-Doniach model [25,26], PIME - area, where both the GL and LD descriptions are broken. In the latter case, which corresponds to shrinking of the Cooper pairs "sizes" by a magnetic field, our Eqs. (6)-(14) are still valid and the Reentrant Superconducting (RS) phase appears. The RS phase may reveal itself as an increase of the transition temperature in a magnetic field, if the orbital effects of an electron motion are stronger than the Pauli spin-splitting effects (dashed line). The RS phase always reveals itself as a paramagnetic intrinsic Meissner effect (PIME), which results in unexpected in-plane anisotropy of the upper critical field and magnetization even in the case, where the Pauli spin-splitting effects are strong and, thus, the area with $dT_c/dH > 0$ is absent (solid line). We suggest to measure in-plane torque, the upper critical field, and magnetization to discover the RS phase.

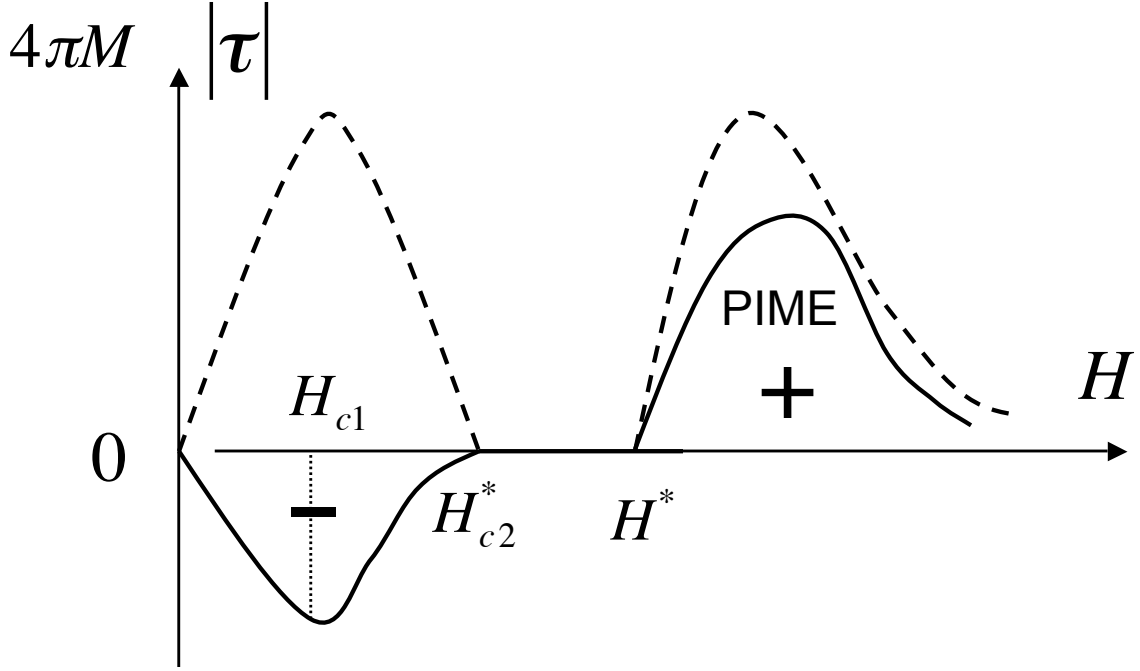


FIG. 2: Solid line: in-plane magnetization, $4\pi\mathbf{M}$, is sketched as a function of a magnetic field in the absence of the Pauli spin-splitting effects. At high magnetic fields, $H \geq H^*$, the Reentrant Superconducting (RS) phase reveals itself as a paramagnetic intrinsic Meissner effect (PIME). Dashed line: an absolute value of in-plane torque, $|\tau|$, is sketched. It is important that the torque is independent on the Pauli spin-splitting effects since they are isotropic. Therefore, even in the case, where the destructive Pauli spin-splitting effects eliminate a positive sign of the Meissner effect in high magnetic field, the PIME phenomenon and the RS phase can still be detected by the in-plane torque measurements.